Forest landowner decisions and the value of information under fire risk

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Abstract: We estimate the value of three types of information about fire risk to a nonindustrial forest landowner: the relationship between fire arrival rates and stand age, the magnitude of fire arrival rates, and the efficacy of fuel reduction treatment. Our model incorporates planting density and the level and timing of fuel reduction treatment as landowner decisions. These factors affect, among other things, the loss a landowner incurs should fire arrive before harvesting. The value of information depends on the nature and combination of mistakes a landowner makes, the relationship between fire arrival and stand age, and on whether the landowner undertakes fuel treatment and values nontimber benefits. Information of various types is of most value to a landowner who does not undertake fuel treatment. The value of information about the magnitude of fire risk is also more than twice as high when the landowner underestimates fire risk, rather than overestimating it. For a landowner who undertakes fuel treatment but makes multiple mistakes, the asymmetry between overestimating and underestimating fire risk and efficacy of fuel reduction is even more pronounced.

Résumé : Nous avons estimé la valeur de trois types d'informations au sujet des risques d'incendie pour un propriétaire de forêt non industrielle : la relation entre le taux d'occurrence du feu et l'âge du peuplement, l'ampleur du taux d'occurrence du feu et l'efficacité des traitements pour réduire les combustibles. Notre modèle incorpore les décisions du propriétaire concernant la densité de la plantation ainsi que l'ampleur et le moment des traitements de réduction des combustibles. Ces décisions affectent entre autres choses les pertes encourues par un propriétaire si un feu survient avant la récolte. La valeur de l'information dépend de la nature et de la combinaison des erreurs que commet un propriétaire, de la relation entre l'occurrence du feu et l'âge du peuplement et du fait que le propriétaire entreprenne ou non des traitements de réduction des combustibles et accorde ou non une valeur aux produits non ligneux. Différents types d'informations ont une grande valeur pour le propriétaire qui n'entreprend pas de traitements de réduction des combustibles. La valeur de l'information au sujet de l'importance du risque d'incendie est également deux fois plus élevée lorsque le propriétaire sous-estime le risque d'incendie plutôt que de le surestimer. Dans le cas d'un propriétaire qui entreprend le traitement des combustibles mais fait plusieurs erreurs, l'asymétrie entre la surestimation et la sous-estimation du risque d'incendie et l'efficacité de la réduction des combustibles est encore plus prononcée.

[Traduit par la Rédaction]

Introduction

Incorporating better information into economic decisions is an active research area within the natural resource economics literature (Adams et al. 1984; Peck and Richels 1987; Gillmeister et al. 1990; Costello et al. 1998; Fox et al. 1999; Bontems and Alban 2000). The interest is often, first, to determine how information affects decisions and, second, to estimate a "value" of improved information to the decision maker. This work has been applied primarily to pest management and agricultural decision making, where uncertainty regarding future weather or pest attacks results in costly errors in input use by producers. There is also a voluminous general economics literature related to the value of information in decision making (recent examples include Gersbach 1997; Craft 1998; Lawrence 1999; Morris and Song 2002). In most cases, this value is estimated as the cost avoided by making better-informed decisions.

The many recent forest fires in the United States have precipitated discussion about government efforts to encourage landowners to reduce fuels on their properties. Information certainly has a role in this debate. Landowners with improved information would realize the value of fuel reduction efforts that can minimize fire losses, and they would be more likely to use fuel reduction efficiently (Society of American Foresters 2000, 2002). Fuel reduction undertaken during a rotation can include activities such as burning of surface fuels, pruning, and clearing of underbrush, most of which do not yield merchantable timber. Often landowners do not know that these forest management decisions affect fire losses. Landowners also must make decisions with an imperfect knowledge of the probability of fire arriving on their forest land (Society of American Foresters 2000, 2002).

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In this paper, we estimate the value of several types of improved information about fire arrival (or occurrence) probabilities and fuel reduction efficacy to a nonindustrial private forest landowner. We use a now standard repeating-rotations model of a nonindustrial forest landowner making decisions under risk of fire. Our model incorporates the following landowner decisions: the timing of fuel reduction during a rotation, the level of this reduction, planting density, and rotation age. We model different time paths for the probability of fire arrival during a rotation, and we allow for the possibility that some timber is salvaged if fire strikes before the end of a rotation. In the spirit of empirical work on nonindustrial landowner behavior, we also assume that the landowner values both timber income and nontimber uses of their forest.

Our focus on a nonindustrial private landowner reflects the fact that this ownership class is most common in many parts of the United States where fire is important (Society of American Foresters 2002; Pattanayak et al. 2002; Amacher et al. 2003; Kuuluvainen et al. 1996). Existing work has not specifically considered many aspects of fire risk faced by these landowners. For example, existing models have shown how rotation age depends on risk of fire or other loss, but landowners have not been assumed to value nontimber forest uses (Reed 1984). Fuel reduction also has not been studied extensively as a landowner decision, yet this choice can affect losses to the landowner should fire occur.

Some exceptions are Englin et al. (2000), who show how rotation-age decisions, made under risk of fire, depend on simulated nontimber benefits, as well as Reed (1987) and Reed and Apaloo (1991). Reed (1987) considered the choice of annual fire prevention expenditures as a means of reducing fire arrival rates, but he did not link fuel reduction decisions specifically to salvage, allow for nontimber benefits, or estimate the value of information. Our model also differs by assuming a landowner engages in a more common discrete fire prevention schedule that includes one-time activities such as prescribed burning. These decisions are more relevant for nonindustrial landowners who do not typically invest in their forests on a continuous basis. Finally, in a model without fuel reduction, Reed and Apaloo (1991) consider how planting density could be chosen in the face of fire risk, but they do not consider the value of information.

There is no work we are aware of that estimates the value of information for a forest landowner who makes decisions under uncertainty about future fire risk parameters. Knowing the value of information in fire management problems could certainly add to the ongoing discussion in many countries concerning the design of government interventions to ensure that landowners make management decisions in ways that reduce fire losses (e.g., see Society of American Foresters 2002). A private landowner's decisions certainly affect the level of costly fire-control effort expended by a government. The landowner does not bear this cost completely, and thus the behavior of a landowner is likely to diverge from decisions the government would make. Our work is suggestive of how information can reduce this divergence between landowner and government incentives.

The rest of the paper is organized as follows. First, we discuss a model of nonindustrial landowner behavior under imperfect information about fire arrival.[2] Second, we present a simulation, based on the model, to estimate the value of three types of information. Finally, we offer some concluding remarks.

Landowner model

Our model of a nonindustrial landowner follows the well-known multiple repeating rotations framework of Reed (1984) and others, but we generalize it to include both initial planting density and fuel reduction decisions. In what follows, we will refer to fuel reduction as an "intermediate treatment" to reflect the fact that it is undertaken during a rotation.

There are three types of information a landowner needs in our model. First, the landowner must know the relationship between fire probabilities and stand age — we examine two possible cases for this relationship. Second, the landowner must know the magnitude of the fire probability throughout the rotation. Finally, the landowner must understand the relationship between intermediate treatment and fire loss.

Fire risk and loss

Following Reed (1984) and others, fires arrive randomly over time in our model. The probability of fire arrival is assumed to follow a Poisson process with parameter λ, which captures the average fire (event) arrival rate; more specifically, λ defines the probability that fire occurs at a given time during the rotation. Two cases are examined for completeness. First, we assume that the fire arrival rate is constant over time, implying a constant λ; this is similar to assuming that the fire probability distribution amounts to a random walk consistent with inherently unpredictable weather and demographic-related effects on fire occurrence. Second, we allow for the possibility that the fire arrival rate increases with stand age, so that $\lambda = \lambda(X)$ and $\lambda'(X) > 0$.

The time between fire arrivals during any rotation is an exponential random variable, X, with cumulative distribution function $(1 - e^{-m(X)})$, where $m(X) = \int_0^X \lambda(u)\,du$, and u is a variable of integration. The corresponding probability density function for X is $\lambda(X)\,e^{-m(X)}$. Given a rotation age of T, the probability that a fire arrives before the end of a rotation is $\Pr(X < T) = (1 - e^{-m(T)})$. The probability that the stand reaches its rotation age and is "destroyed" through harvesting is then $\Pr(X = T) = e^{-m(T)}$. Previous economic studies of fire risk in Faustmann-type models also use the Poisson assumption and this probability structure (Stainback and Alavalapati 2004; Amacher et al. 2005; Englin et al. 2000; Fina et al. 2001; Reed 1984, 1987). Reed (1984) and Reed (1987) further consider, like we do, a fire arrival process where the probability of fire can depend on the age of the stand.

As noted earlier, the landowner makes four choices: the level of intermediate treatment (z), stand age when this treatment is applied (s), planting density (d), and rotation

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[2] In another separate article, we develop the framework of landowner decision making under risk of fire used here, considering several additional versions of our basic model (Amacher et al. 2005). However, we do not examine the value of information in the other article.

age (T). Planting at lower densities might be considered to be a weak form of fuel reduction in our model. Following other work in Faustmann-based fire models (examples are Reed 1984; Englin et al. 2000; Amacher et al. 2005), we assume that the landowner plants and begins a new rotation whenever a fire arrives, ad infinitum; thus, X also represents stand age at the time of fire arrival.[3] However, unlike other work, if a fire arrives during a rotation after intermediate treatment is applied ($X \geq s$), we assume that the landowner salvages and sells some proportion of timber. With the exception of Reed (1984), who allows for random salvage that does not depend on landowner decisions, most previous work ignores the possibility of salvage opportunities in a landowner model.

Once fire arrives, salvage is assumed to depend on both intermediate treatment and planting density (planting density also affects timber yield directly, as we discuss below). The salvageable fraction of timber is described by a concave function of planting density and intermediate treatment effort, $k(z,d)$. We assume that intermediate treatment increases salvageable timber, $\partial k(.)/\partial z \geq 0$. We also assume, conservatively, that no intermediate treatment leads to no salvage in the event of fire, i.e., $k(0,d) = 0$. Planting at higher densities potentially increases the severity of fire and reduces salvageable materials, $\partial k(.)/\partial d \leq 0$. Finally, salvage by an individual landowner is assumed to be too small to affect market prices for timber.

Our assumption regarding fire arrival and salvage requires further discussion. In our model, intermediate treatment affects salvage (fire loss) once fire occurs, but it does not affect the probability that a fire arrives on the stand under study. Fuel reduction in single stand is more likely to affect the severity of fire once it arrives, because most fires arrive on an individual landowner's land regardless of whether fuel reduction was undertaken or not. Consider a lightning strike on a specific tree, or a fire arriving on the landowner's forest through flying embers or root systems from a burning adjacent area (the most common form of arrival for any single nonindustrial landowner). However, once a tree or brush in the stand ignites, the fire damages the stand according to fuel that is present. Thus, fires arrive in these cases regardless of the fuel situation, but what happens after they arrive depends on fuels that are present.

There is support for this assumption in the literature. A recent survey concluded that burning of fuels (an important fuel reduction activity) is most likely only to affect fire severity (e.g., see Fernandes and Botelho 2004). The authors further conclude that there is not enough evidence to suggest that burning has any significant effect on the probability of fire arriving in a stand. Our assumption is also consistent with literature advocating intermediate treatment for fire loss reduction in the event of fire (Wade and Lundsford 1990), and it is the basis for forest property insurance, according to a recent US Forest Service report (USDA Forest Service 2003).

One advantage of our intermediate treatment – fire arrival assumption is that the value of information we estimate amounts to a lower bound. The value of making better-informed decisions would likely be greater than we report here if intermediate treatment were assumed to affect both the probability of fire arrival and fire losses.

Expected rents

Forest volume at harvest is assumed to be a concave function of rotation age and planting density, $V(X,d)$, where $\partial V(.)/\partial X > 0$ and $\partial V(.)/\partial d > 0$. Little is known about whether intermediate treatment affects forest volume. Given that intermediate treatment covers strategies such as brush removal and burning of surface fuels, it is safe to assume that z does not affect harvest volume. Indeed, the effects of burning of surface fuel and other fire protection activities on volume have been deemed inconclusive at best (Waldrop et al. 1987; Waldrop 1997). We therefore assume that $V(.)$ does not depend on z.

The landowner is assumed to value nontimber benefits. These are introduced in a conventional manner, following Hartman (1976) and Englin et al. (2000), by specifying a present value function for periods with no harvesting, $\delta \sum_0^t B(t) e^{-rt} dt$, where $B(.)$ is the annual nontimber benefit, r is the interest rate, and δ is the weight attached to nontimber benefits by the landowner ($0 \leq \delta \leq 1$). Nontimber benefits are assumed not to depend on z, mainly because previous research does not provide any quantitative evidence concerning this relationship.

Let Y denote the landowner's current value of cash flow, or net rent. This is a random variable in our model because it depends on the arrival of fire. There are three possible realizations for Y. If a fire occurs at $X < s$, i.e., before intermediate treatment is applied, then the landowner loses all of the existing stock and incurs a cost of reestablishing a new forest:

$$[1] \qquad Y_1 = e^{rX} \delta \int_0^X B(t) e^{-rt} dt - c_2(d) \qquad \text{if } X < s$$

where $c_2(d)$ is the cost of planting per acre on burned land.

If fire occurs during the time interval $s \leq X < T$, i.e., after intermediate treatment has been applied but before the rotation age is reached, then the landowner salvages a portion of stock, incurs the cost of reestablishment, and incurs a compounded cost of z previously incurred at time s:

$$[2] \qquad Y_2 = pk(z,d) V(X,d) + e^{rX} \delta \int_0^X B(t) e^{-rt} dt - c_2(d) - c(z) e^{r(X-s)} \qquad \text{if } s \leq X < T$$

where p is timber harvest price, taken exogenously by the landowner, and $c(z)$ is the compounded cost of intermediate treatment paid at time s.

Finally, if the rotation period T is reached without fire arriving, then the landowner harvests all of the timber stock, incurs the cost of establishing a new forest, and incurs the compounded cost of z paid at time s:

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[3] While we could assume that the landowner continues a rotation after fire, we evaluate the case of total loss here. Our model therefore applies to the case where fires are severe. Partial losses and continuing rotations are an interesting case for future research.

$$[3]\qquad Y_3 = pV(T,d) + \mathrm{e}^{rX}\,\delta\int_0^T B(t)\,\mathrm{e}^{-rt}\mathrm{d}t - c_1(d) - c(z)\,\mathrm{e}^{r(T-s)} \qquad \text{if } X = T$$

where $c_1(d)$ is the cost of planting per acre on unburned land.

Using [1]–[3], the landowner maximizes expected net discounted rents for an infinite series of rotations:

$$[4]\qquad M(d^*, z^*, s^*, T^*) \equiv \mathrm{Max}_{d,z,s,T}\,\frac{E(\mathrm{e}^{-rX}Y)}{[1-E(\mathrm{e}^{-rX})]} - c_{\mathrm{I}}$$

where c_{I} is initial planting cost, and the star superscript denotes the optimal value of each decision variable. Expanding the right-hand side of [4] using [1]–[3] we have

$$[5]\qquad M(d^*, z^*, s^*, T^*) \equiv \mathrm{Max}_{d,z,s,T}\,\frac{\int_0^s \lambda(X)\,\mathrm{e}^{-m(X)}\mathrm{e}^{-rx}Y_1\,\mathrm{d}X + \int_s^T \lambda(X)\,\mathrm{e}^{-m(X)}\mathrm{e}^{-rX}Y_2\,\mathrm{d}X + \mathrm{e}^{-m(T)}\mathrm{e}^{-rT}Y_3}{r\int_0^T \mathrm{e}^{-m(X)-rX}\,\mathrm{d}X}$$

The denominator of [5] has been simplified using the probability distribution for X. First-order conditions for this problem are complicated, and general comparative statics results cannot be derived — both Reed (1984) and Englin et al. (2000) found this to be true in much simpler models with rotation age as the only choice variable. We will therefore rely on a simulation to examine qualitative features of the model.

Computing the value of information

As noted earlier, the landowner requires three types of information. The first is the relationship between the average fire arrival rate and stand age. If the landowner has accurate information, then it is assumed he knows that the arrival rate increases as stand age increases. Being uninformed in this case implies that the landowner behaves as if the fire arrival rate is constant over time, so that $\lambda(t) = \lambda$ in [1]. The second type of information needed by the landowner is the magnitude of the fire arrival rate. The landowner is unlikely to be aware of its precise magnitude. Accordingly, we consider the consequences of underestimating and overestimating the fire arrival rate. Finally, it is well known that landowners may not know the extent to which intermediate treatment affects fire losses (Society of American Foresters 2002). Inaccurate information about intermediate treatment can be captured by assuming the landowner either underestimates or overestimates the contribution of z to the salvage function $k(z,d)$.

The value of information is defined as the difference in the maximum present value of rents with and without accurate information. Suppose the true information set is ψ^*. Then, referring to [4], $M(d^*,z^*,s^*,T^*;\ \psi^*)$ is the maximum expected rent when decisions are made optimally given accurate information. Let $M(d_0,z_0,s_0,T_0;\ \psi^0)$ denote maximum expected rents when decisions are made optimally using an "inaccurate" information set ψ^0. The value of information is simply the difference in these rents:

$$[6]\qquad M(d^*, z^*, s^*, T^*; \psi^*) - M(d_0, s_0, T_0; \psi^0)$$

Later in the paper, we will also make use of $M(d_0,z_0,s_0,T_0;\ \psi^*)$, which represents the maximum present value of rents when evaluated at suboptimal decisions (made using information set ψ^0) when the actual information set is ψ^*; necessarily, $M(d_0,z_0,s_0,T_0;\ \psi^*) < M(d^*,z^*,s^*,T^*;\ \psi^*)$.

Simulation

It is useful to define three types of landowners for comparison purposes. First, we consider a "partial prevention" landowner who makes only rotation-age and planting decisions but does not undertake intermediate treatment ($z = s = 0$). Second, we consider a "full prevention" landowner who makes all decisions (T, z, d, s) but is assumed not to value nontimber benefits, $\delta = 0$. Finally, we consider "full prevention with nontimber benefits" landowner who makes all decisions but for whom $\delta = 1$. It is worth noting that our comparison of full and partial prevention landowners will show what a landowner would gain switching from partial to full prevention behavior, to the extent that information might encourage such a switch.

The simulation was based on loblolly pine (*Pinus taeda* L.), an economically important U.S. softwood species, given the availability of data. Functional forms, presented in Table 1, were chosen according to theory and available published evidence.[4] Previous literature provides adequate guidance for the forest volume function, simulated nontimber benefit function, and planting costs. Marginal costs for establishing trees (dollars per acre, 1 acre = 0.4047 ha) on burned and unburned land are taken from Dubois et al. (2001). Stumpage prices (dollars per thousand board feet of pine sawtimber) are obtained from Timber Mart-South (2002). The marginal cost of replanting burned land (dollars per acre) is less than the marginal cost of replanting unburned land because the

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[4] The program used for the simulation is MATLAB version 6.1, with optimal values determined using search algorithms applied to the appropriately defined objective functions. As mentioned earlier, the first-order conditions for the problem considered are very unwieldy. Rather than deriving the first-order conditions and numerically solving them, we used gradient-free, global search algorithms for finding the solution to each problem. Two algorithms were used: MATLAB's built in fminsearch routine, which employs a simplex search routine, and the public domain plug-in for MATLAB, gblsolve, which is a global optimization routine that relies on Lipschitzian optimization (see Jones et al. 1993).

Table 1. Functional forms and base values of parameters in simulations.

Type	Function	Assumed form
Timber volume	$V(X,d)$	$\alpha - \frac{\beta_1}{dX} - \frac{\beta_2}{XS} - \frac{\beta_3}{X^2} - \frac{\beta_4}{S^2}$ ($\beta_1 = 3418.11$, $\beta_2 = 740.82$, $\beta_3 = 34.01$, $\beta_4 = 1527.67$, $\alpha = 9.75$, $S = 80$)
Average fire arrival rate function	Constant average arrival rate, λ	$\lambda = \frac{t_0}{t_b - t_a}$ ($t_a = 0$, $t_b = 50$)
	Rising average arrival rate, $\lambda(X)$ with $\lambda > 0$	$\lambda(X) = 2t_0 \frac{(X - t_a)}{(t_b - t_a)(t_c - t_a)}$ ($t_a = 0$, $t_b = t_c = 50$)
Nontimber benefits	$B(t)$	$b_0\, e^{-b_1 t}(b_0 = 8/60,\ b_1 = 1/60)$
Planting costs	$C_1(d)$, unburned land	$c_1 d$ ($c_1 = 0.42$)
	$C_2(d)$, burned land	$c_2 d$ ($c_2 = 0.30$)
Timber salvage	$k(d,z)$	$k_0\left(1 - e^{\frac{-k_1(k_2+z)}{d}}\right)$ ($k_0 = 0.9936$, $k_1 = 2/3$, $k_2 = 1$)
Cost of intermediate fuel treatment	$C_3(z)$	$c_0 + c_3 z(c_0 = 5,\ c_3 = 0.04)$

soil requires less preparation (Dubois et al. 2001). The volume function (board feet per acre) is taken from the Faustmann-based literature (Chang 1984; Amacher et al. 1991). With reference to Table 1, a base age 25 site index of 80 feet (1 foot = 0.3048 m) ($E = 80$) is used for the harvest volume function. The nontimber benefit function reflects benefits that increase over time in a forest stand and are similar to those studied in Swallow et al. (1993), Swallow et al. (1997), and Vincent and Boscolo (2000). This function peaks at age 60, which for loblolly pine is consistent with old-growth values attached to pine forests, such as habitat values for woodpeckers.[5] For an increasing arrival rate, a triangular distribution is used to specify $\lambda(t)$ (see Freund and Walpole 1980, pp. 243–244). In Table 1, notice that changes in the scale parameter t_0 simulate a shift in the magnitude of the fire arrival rate.

No published information is available for some of the functions needed in the simulation, so we proceed with functional forms having plausible shapes and reasonable baseline values for decisions. The timber salvage function $k(.)$ reflects diminishing returns, yields reasonable fractions when evaluated at its arguments, and is bounded by zero and one. Total costs of intermediate treatment are assumed to have both variable and fixed components, given that this treatment could involve varying labor and equipment needs; in the simulation, these total costs range from \$22 to \$40, with larger values at higher magnitudes for the fire arrival rate. This range is consistent with per-acre costs of activities such as burning of surface fuels in the southeastern United States (Dubois et al. 2001).[6] The interest rate is assumed to be 5%.

Simulation results

Baseline simulation results for all model variants along with units of measurement are presented in Table 2.[7] Our main interest is in computing the value of information, and thus we will not spend much time discussing the baseline results (see Amacher et al. (2005) for a discussion). Intermediate treatment is measured in units of effort. The "expected rents" column gives the present value of maximum expected rents of the landowner (dollars per acre), which is the value of $M(.)$ in [4] when evaluated at optimal choices. Also shown are salvage proportions when decisions are

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[5] Whenever nontimber benefits were included, the concavity of the objective function was checked. The value of nontimber benefits per year in our simulation was calibrated according to assumptions used elsewhere in the southern United States (Wear and Greis 2002). We examined several alternative peak ages and paths for nontimber benefits in the simulation, and we examined the implications for these benefits for both partial and full prevention landowners. Alternative paths did not make significant differences in our value of information estimates, and including nontimber benefits for a partial prevention landowner affects value of information in the same way as a full prevention landowner. Results are available from the authors upon request.

[6] It is possible that the costs of intermediate treatment undertaken in an existing mature stand could be significantly higher than our total cost of z; however, our use of a repeating-rotations model assumes the landowner begins with bare land, so that intermediate treatment is done when the stand is relatively young. Allowing a landowner to start with an existing mature stand, which would have a high cost of intermediate treatment, would not be difficult but would unnecessarily complicate notation without adding new insights.

[7] The fminsearch routine in MATLAB was efficient at finding solutions given an appropriate set of starting values. The latter were typically derived using the gblsolve routine, which we found to be adept at getting very close to the solution given very wide intervals over which to search. For each basic scenario that we considered, we verified that the solutions identified did, in fact, yield global maxima by conducting sensitivity analyses and by plotting the objective function in each choice variable. Despite the complexity of our model, we found that the objective function had only minor non-concavities.

Table 2. Baseline choices, salvage, and rents.

Model	t_0	$m(T^*)$	T^*	d^*	s^*	z^*	$k(d^*,z^*)$	Expected rents ($/acre)
Partial prevention								
Constant arrival	1	0.43	21.5	308				163
	2	0.84	20.9	228				62
	3	1.08	21.6	149				7
Rising arrival	3.2	0.43	18.3	313				131
	7.8	0.84	16.4	221				10
	10.2	1.08	16.3	170				–26
Full prevention								
Constant arrival	1	0.49	24.7	300	9.9	498	0.67	173
	2	1.10	27.6	244	9.6	680	0.84	103
	3	1.83	30.5	200	9.9	673	0.89	44
Rising arrival	2.2	0.49	23.7	322	10.3	669	0.75	189
	4.3	1.10	25.4	294	9.8	883	0.86	144
	6.5	1.83	26.6	274	9.5	932	0.89	103
Full prevention with nontimber benefits								
Constant arrival	1	0.52	25.8	295	10.7	533	0.70	210
	2	1.16	29.1	239	10.6	707	0.86	140
	3	1.96	32.7	192	11.4	690	0.90	81
Rising arrival	2.15	0.52	24.6	319	10.7	706	0.77	225
	4.16	1.16	26.5	292	10.1	913	0.87	180
	6.32	1.96	27.9	273	9.9	957	0.90	138

made optimally. The "constant arrival" and "rising arrival" rows of the table correspond to fire arrival rates that are constant and increasing with stand age, respectively. With reference to Table 1, changes in t_0 are directly and linearly related to changes in the magnitude of the arrival rate for all stand ages.

The first three rows of the partial prevention results in Table 2 are for a constant fire arrival rate. In the first of these rows ($t_0 = 1$), we assume that the average arrival rate, λ, takes on a value of 1/50 ($t_0/50$), i.e., a fire arrives on average once every 50 years. The next two rows show the effects of increases in fire risk. With $t_0 = 2$, λ takes on a value of 2/50 ($t_0/50$), and with $t_0 = 3$, λ takes on a value of 3/50. The third column in Table 2, labeled $m(T^*)$, is the resulting cumulative average fire arrival rate (or cumulative probability of a fire occurring) from time zero to the optimal rotation age. The value of $m(T^*)$ increases with t_0, but it is important to note that values of $m(T^*)$ reflect both an increase in t_0 and a change in optimal rotation age T^*. Thus, a doubling of t_0 from one to two does not result in a doubling of $m(T^*)$ — the doubling of t_0 is partially offset by the fall in T^*.

Finally, the three rows labeled "rising arrival" present results for a rising average arrival rate with stand age. To be able to compare these results with those for the "constant arrival" case, the parameter t_0 was chosen so that the cumulative arrival rate of fire at rotation age $m(T^*)$ was approximately the same as in the corresponding "constant arrival" case. Not choosing t_0 in this manner would imply that the aggregate level of fire risk over a rotation differs for the two cases, making it difficult to attribute changes in the optimal values of the decision variables to changes in the shape of the arrival path alone.

Our partial prevention landowner results show that fire risk dramatically lowers planting density, justifying its inclusion as a choice variable in our model. For the rising arrival case but not the constant arrival case, higher fire risk also lowers rotation age, and maximum expected rents are lower.

When the landowner is assumed to choose intermediate treatment (the full prevention landowner), maximum rents do not fall as much when fire risk increases, and planting density decreases are not as large. We also see, under a rising arrival rate, that intermediate treatment increases dramatically for higher fire arrival rates. This follows because intermediate treatment represents an additional means for the landowner to defend himself against increased fire risk, through the effect of z on salvage. The timing of treatment ranges from 9 to 11 years and is consistent with treatment ages recommended in practice for activities such as burning of fuels and brush removal (Wade and Lundsford 1990). It is also interesting that the level of intermediate treatment is more sensitive to fire risk than the timing of treatment (s changes very little, particularly for the constant arrival case). Rotation ages are now increasing in fire risk for both constant and rising arrival rate cases. This occurs because intermediate treatment, which increases salvage (see the last column of the table), reduces the risk associated with longer rotations. Essentially, intermediate treatment decreases the marginal expected cost of continuing a rotation under fire risk. The basic results do not change much with the inclusion of nontimber benefits.

Value of information about fire risk

The responsiveness of intermediate treatment to changes in the fire arrival rate suggests that improved information

Table 3. Value of information about relationship between stand age and fire arrival rate (t_0).

Model	Fire arrival rate	t_0	Expected rents ($/acre): If constant relationship assumed	Expected rents ($/acre): With correct relationship	Increase in rents ($/acre)	% increase in rents
Partial prevention	0.02	3.20	117	131	14	12.0
	0.04	7.80	–18	10	28	Undefined
	0.06	10.2	–45	–26	19	Undefined
Full prevention	0.02	2.20	185	189	4	1.8
	0.04	4.27	138	144	6	4.4
	0.06	6.45	91	103	12	12.9
Full prevention with nontimber benefits	0.02	2.15	222	225	3	1.5
	0.04	4.16	173	180	6	3.6
	0.06	6.32	124	138	14	11.1

about fire risk could encourage landowners to undertake such treatment at higher levels. It also suggests that previous fire models that do not include planting density and intermediate treatment as choice variables ignore decisions that will change as landowners become better informed.

Fire arrival rate and stand age

Suppose a landowner mistakenly believes that the arrival rate is constant when in fact it is rising with stand age. The landowner's mistaken choices and expected rents are given by the values in Table 2 for the constant arrival case and relevant value of t_0. Table 3 presents the value of information for different values of t_0.[8] The rents reported in the fourth column labeled "expected rents if constant relationship assumed" are actual expected rents obtained by substituting the landowner's (suboptimal) choices, solved under the mistaken perception of a constant arrival rate, into the objective function in [4] that incorporates the correct arrival rate. Thus, the first value in this column, $117, is obtained by taking the values of the choice variables in the first row of Table 2 and substituting them into an objective function that reflects a rising arrival rate with the scaling parameter t_0 set equal to 3.20, so that the aggregate level of risk, as captured by $m(T^*)$, is the same for the constant and rising arrival scenarios. The expected rents a landowner would have earned had he known that the arrival rate is increasing with stand age (with $t_0 = 3.2$) are reported in the "expected rents with correct relationship" column; these rents are identical to those given in Table 2 for this case and represent the value of [4] when evaluated at the optimal decisions solved under the correct arrival rate. The last two columns show the absolute and relative increases in maximum expected rents from having accurate information about the relationship between fire arrival and stand age. These are obtained using [6], i.e., by subtracting table elements in the fourth column from elements in the fifth column.

When the models in Table 3 are compared, the value of information is highest, and quite substantial, for a landowner who does not employ intermediate treatment, i.e., for the partial prevention landowner. Having accurate information about fire arrival probabilities as a stand ages would enable this landowner to increase expected rents by $14 to $28 per acre. At very high fire risk levels, i.e., $t_0 = 7.8$ and above, inaccurate information could be the difference between a landowner choosing to continue in forest production or abandoning it, as expected rents are negative for the partial prevention landowner. For the full prevention landowner the value of information is quite small in all cases. This results because this landowner is able to shield himself against having poor information through better salvage possibilities if fire arrives.

Interestingly, the presence of nontimber benefits reduces the absolute magnitude of the value of information when intermediate treatment is undertaken, though only by less than 2%. Information about fire arrival appears less important when nontimber benefits are present, because in our model fire does not diminish the stream of nontimber benefits received in any time period.

The high value of information observed for the partial prevention landowner given rising fire arrival rates can be explained as follows. Recall we found in Table 2 that the reductions in maximum expected rents due to fire risk were highest in this case, because the landowner does not have the option of using intermediate treatment to shield himself against risk. For this type of landowner, having better information about fire risk is most important, because he can vary only planting and rotation-age decisions to reduce risk of loss. A rising fire arrival rate makes mistakes more costly in this case simply because rotation ages cannot be shortened too much without reducing the value of harvested timber. Thus, the marginal benefit of improved information is higher for this landowner.

Magnitude of fire risk

In terms of our simulation, a landowner misinformed about the fire arrival rate is equivalent to a landowner not knowing t_0 with accuracy. Decisions for a landowner who either overestimates or underestimates the average arrival rate are shown in Table 4A, assuming t_0 is varied by plus or minus 50% from the baseline value found in the middle of each grouped row of values in Table 2. Here, it is no longer possible to keep the aggregate level of fire risk, $m(T^*)$, identical across constant and rising arrival rate cases. Thus, the results in Table 4A differ slightly from those found in Table 2. The

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[8] For the partial prevention landowner in Table 3, some cases of higher fire risk resulted in a negative expected rent. For these cases, entries for the column "% increase in rents" are labeled as undefined.

Table 4. (A) Effects of changes in fire arrival rates (t_0) and (B) value of information about fire arrival rate.

(A) Effects of changes.

Model	t_0	T^*	d^*	s^*	z^*	$k(d^*,z^*)$	Expected rents ($/acre)
Partial prevention							
Constant arrival	1	21.5	308				163
	2	20.9	228				62
	3	21.6	149				7
Rising arrival	3.9	17.8	298				106
	7.8	16.4	221				10
	11.7	0.0	0				0
Full prevention							
Constant arrival	1	24.7	300	9.9	498	0.67	173
	2	27.6	244	9.6	680	0.84	103
	3	30.5	200	9.9	673	0.89	44
Rising arrival	2.135	23.6	323	10.3	657	0.74	191
	4.27	25.4	294	9.8	883	0.86	144
	6.405	26.6	275	9.5	932	0.89	104
Full prevention with nontimber benefits							
Constant arrival	1	25.8	295	10.7	533	0.70	210
	2	29.1	239	10.6	707	0.86	140
	3	32.7	192	11.4	690	0.90	81
Rising arrival	2.08	24.5	320	10.7	693	0.76	227
	4.16	26.5	292	10.1	913	0.87	180
	6.24	27.8	274	9.9	957	0.90	139

(B) Value of information.

		Expected rents ($/acre)				
Model	True value of t_0	If rate underestimated by 50%	If rate overestimated by 50%	If rate known accurately	Increase in rents ($/acre)	% increase in rents
Partial prevention						
Constant arrival	2.00		48	62	13	27.5
		50		**62**	**12**	**23.3**
Rising arrival	7.8		0	10	10	Undefined
		–7		**10**	**17**	Undefined
Full prevention						
Constant arrival	2.00		99	103	5	4.8
		93		**103**	**11**	**11.7**
Rising arrival	4.27		142	144	1	0.8
		137		**144**	**6**	**4.7**
Full prevention with nontimber benefits						
Constant arrival	2.00		135	140	5	3.6
		130		**140**	**10**	**8.0**
Rising arrival	4.16		179	180	1	0.6
		174		**180**	**6**	**3.4**

Note: Results for underestimating rate by 50% in bold; results for overestimating rate by 50% in regular font.

corresponding value of information is reported in Table 4B, where expected rents under the different cases are computed using the same procedures as before, and the value of information is computed from these rents using [6]. In computing the value of information here, we assume that the landowner knows the correct relationship between fire arrival rates and stand age; thus, the landowner makes only one mistake at a time — we return to multiple mistakes later in the article.

The bolded values in Table 4B represent cases where a landowner underestimates fire risk while nonbolded values represent cases where the landowner overestimates fire risk. As the table shows, this type of information is most valuable for the partial prevention landowner when the fire arrival rate is constant. This is similar to our earlier results, in that a landowner who undertakes partial prevention has less opportunity to reduce fire losses, and thus risk of loss and the importance of accurate information to him are higher. For a full prevention landowner, the value of information is lower but still positive. When arrival rates are constant, this type of landowner gains about 5%–12% in expected rents from having accurate information if he underestimates fire risk.

Information continues to be of some (albeit smaller) value for a full prevention landowner who values nontimber benefits. In the constant arrival case, accurate information yields increases in expected rents ranging from 3% to 8%. The slight reduction in importance of information might be explained as follows: The presence of nontimber benefits provides an additional benefit of holding forest stock, regardless of fire risk. Thus, mistakes made about the magnitude of fire risk are not as critical, proportionally, given that nontimber benefits accruing to the forest stock over time can be a significant part of the landowner's overall expected rent.

Finally, note that in most cases, the value of information about magnitude of fire risk is consistently at least twice as high when the landowner underestimates fire risk as when he overestimates it. Clearly, a landowner is better off overestimating fire risk rather than underestimating it.

Value of information about intermediate treatment efficacy

Given the lack of interest landowners appear to have for using intermediate treatment (Society of American Foresters 2002), it is likely that they are unaware of the benefits of such treatment. We model inaccurate information here by assuming that the uninformed landowner either underestimates or overestimates by 50% the contribution of intermediate treatment to salvage. With reference to Table 1, this is accomplished by varying the k_1 parameter 50% below and 50% above its base value used in the simulation ($k_1 = 2/3$). This parameter is directly related to the marginal contribution of intermediate treatment to salvage.

Table 5A presents decisions and maximum expected rents for the full prevention landowner at the three values of k_1 specified above. Notice that for the lowest value of k_1 (= 1/3) and a constant fire arrival rate, we have a corner solution in which it is optimal for the landowner to not undertake intermediate treatment (i.e., $z = 0$). Other than these corner solutions, we observe trends in decisions and rents in Table 5A that are similar to those we noted in Table 2 when comparing across models having the same value of k_1.

Table 5B reports the value of information about intermediate treatment efficacy, again following the earlier procedures to obtain [6] using maximum expected rents. Bolded table elements reflect underestimation of k_1 by 50%, while nonbolded elements reflect overestimation by 50%. Having correct information about k_1 affords the landowner as much as 20.8% higher expected rents when the landowner does not value nontimber benefits and 13.4% higher rents when he does — in each case, the highest percent rent increases occur for higher magnitudes of fire risk.

The value of information about intermediate treatment efficacy is also consistently higher when the landowner underestimates the efficacy. From Table 5A, underestimation typically results in rotations that are too short, planting densities that are too low, and intermediate treatment that is delayed too far into the future. Even at lower levels of fire risk, a landowner who underestimates the effects of intermediate treatment on salvage foregoes considerable rents depending on whether nontimber benefits are valued or not.

Value of information with compounded mistakes

It is quite possible, if not likely, that a landowner could make a combination of mistakes discussed above. The expression in [6] can still be used to compute the value of information for multiple mistakes, but there is now more than one component of information that differs between information sets ψ^* and ψ^0. This yields results that are different from those in the previous tables, where [6] was computed assuming the landowner had inaccurate information about only one component of the true information set ψ^*. We will assume that the true value of k_1 is 2/3, and that the true value of t_0 equals its median value of 4.16 and 4.27 for the full prevention landowner with and without nontimber benefits, respectively. We also restrict attention to cases where the landowner mistakenly perceives the relationship between fire risk and stand age to be constant, when, in fact, fire risk rises with stand age.

Table 6 presents the results. The second and third columns give maximum expected rents with compounded mistakes and with perfect information, respectively, while the last two columns give the absolute and relative increase in expected rents calculated using the second and third columns. The rows define cases in which the landowner either underestimates or overestimates fire risk and the efficacy of intermediate treatment. The expected rents given perfect information are equivalent to the corresponding expected rents found in Table 4A for each case.

The results are striking. When a landowner underestimates both fire risk and the efficacy of intermediate treatment, accurate information yields expected rent increases of 70%–112%, depending on whether the landowner values nontimber benefits or not. A landowner who values nontimber benefits stands to gain less from accurate information, but the increase in maximum expected rent of 69.7% is still substantial. Overestimating fire risk and underestimating intermediate treatment efficacy are also quite costly: increases in maximum expected rents from accurate information here equal 32% and 39.3% depending on whether nontimber benefits are valued or not.

The landowner who benefits the least from accurate information, by far, is one who overestimates both fire risk and the efficacy of intermediate treatment. This landowner will experience increases in expected rents of 11%–14% by having accurate information. Even when fire risk is underestimated, rent increases from accurate information are not as large as long as efficacy of intermediate treatment is overestimated — maximum expected rent rises in this case by 11.6% and 15% when nontimber benefits are and are not valued, respectively.

Perhaps the most important result to take from Table 6 is that a landowner's mistakes are less costly when he overestimates intermediate treatment efficacy than when he overestimates fire risk. This suggests it is more important to disseminate information about the efficacy of intermediate treatment than it is to educate landowners about fire arrival rates.

Table 5. (A) Effects of changes in efficacy of intermediate treatment (k_1) and (B) value of information about efficacy of intermediate treatment.

(A) Effects of changes in efficacy.

Model	k_1	t_0	T^*	d^*	s^*	z^*	$k(d^*,z^*)$	Expected rents ($/acre)
Full prevention								
Constant arrival	1/3	1	21.5	308		0^a	0.00	163
	2/3	1	24.7	300	9.9	498	0.67	173
	1	1	25.1	310	9.1	469	0.63	185
Constant arrival	1/3	2	26.7	218	11.3	780	0.90	76
	2/3	2	27.6	244	9.6	680	0.84	103
	1	2	27.7	260	8.8	576	0.77	118
Constant arrival	1/3	3	30.3	168	12.0	834	0.96	18
	2/3	3	30.5	200	9.9	673	0.89	44
	1	3	30.5	217	9.0	559	0.82	58
Rising arrival	1/3	2.2	20.4	325	11.8	270	0.42	165
	2/3	2.2	23.7	322	10.3	669	0.75	189
	1	2.2	24.4	335	9.6	611	0.70	205
Rising arrival	1/3	4.27	23.1	264	11.1	948	0.90	104
	2/3	4.27	25.4	294	9.8	883	0.86	144
	1	4.27	26.0	314	9.0	754	0.79	164
Rising arrival	1/3	6.45	24.4	234	11.1	1093	0.95	60
	2/3	6.45	26.6	274	9.5	932	0.89	103
	1	6.45	27.6	297	8.8	785	0.82	126
Full prevention with nontimber benefits								
Constant arrival	1/3	1	22.6	303		0^a	0.00	205
	2/3	1	25.8	295	10.7	533	0.70	210
	1	1	26.2	306	9.7	491	0.65	221
Constant arrival	1/3	2	28.5	209	13.1	847	0.93	114
	2/3	2	29.1	239	10.6	707	0.86	140
	1	2	29.1	255	9.6	593	0.78	154
Constant arrival	1/3	3	34.2	146	15.8	859	0.97	60
	2/3	3	32.7	192	11.4	690	0.90	81
	1	3	32.5	211	10.1	571	0.83	94
Rising arrival	1/3	2.15	21.3	318	12.5	387	0.55	199
	2/3	2.15	24.6	319	10.7	706	0.77	225
	1	2.15	25.3	333	9.9	634	0.72	241
Rising arrival	1/3	4.16	24.3	260	11.7	1024	0.92	140
	2/3	4.16	26.5	292	10.1	913	0.87	180
	1	4.16	27.2	313	9.3	773	0.80	200
Rising arrival	1/3	6.32	25.6	231	11.7	1153	0.96	95
	2/3	6.32	27.9	273	9.9	957	0.90	138

(B) Value of information.

		Expected rents ($/acre)				
Model	t_0	If efficacy underestimated by 50%	If efficacy overestimated by 50%	If efficacy known accurately	Increase in rents ($/acre)	% increase in rents
Full prevention						
Constant arrival	1		173	173	1	0.3
		159		**173**	**14**	**9.1**
	2		101	103	2	2.2
		99		**103**	**4**	**4.5**
	3		41	44	3	7.8
		36		**44**	**8**	**20.8**
Rising arrival	2.2		187	189	1	0.8
		179		**189**	**10**	**5.5**
	4.27		140	144	4	2.7

Table 5. (*concluded*).

(B) Value of information.

Model	t_0	Expected rents ($/acre): If efficacy underestimated by 50%	Expected rents ($/acre): If efficacy overestimated by 50%	Expected rents ($/acre): If efficacy known accurately	Increase in rents ($/acre)	% increase in rents
		137		**144**	**7**	**5.1**
	6.45		98	103	5	5.6
		92		**103**	**11**	**12.4**
Full prevention with nontimber benefits						
Constant arrival	1		209	210	1	0.3
		201		**210**	**9**	**4.3**
	2		138	140	2	1.7
		134		**140**	**6**	**4.3**
	3		78	81	4	4.6
		72		**81**	**10**	**13.4**
Rising arrival	2.15		223	225	2	0.7
		217		**225**	**8**	**3.6**
	4.16		175	180	4	2.4
		172		**180**	**8**	**4.6**
	6.32		132	138	6	4.4
		125		**138**	**13**	**10.1**

Note: The actual value of $k_1 = 2/3$; when underestimated by 50%, $k_1 = 1/3$, and when overestimated by 50%, $k_1 = 1$. Results for underestimating efficiacy by 50% in bold; results for overestimating efficacy by 50% in regular font.

[a] Corner solution at which it is optimal for the landowner not to apply intermediate treatment.

Table 6. Value of information with compound errors including incorrect shape of fire arrival path.

Type of compounded error	Expected rents ($/acre): With compound error	Expected rents ($/acre): With perfect information	Increase in rents ($/acre)	% increase in rents
Full prevention[a]				
t_0 and k_2 underestimated by 50%	68	144	76	111.7
t_0 overestimated by 50%; k_2 underestimated by 50%	109	144	65	32.0
t_0 underestimated by 50%; k_2 overestimated by 50%	125	144	19	15.0
t_0 and k_2 overestimated by 50%	126	144	18	14.1
Full prevention with nontimber benefits				
t_0 and k_2 underestimated by 50%	106	180	74	69.7
t_0 overestimated by 50%; k_2 underestimated by 50%	129	180	51	39.3
t_0 underestimated by 50%; k_2 overestimated by 50%	161	180	19	11.6
t_0 and k_2 overestimated by 50%	161	180	18	11.3

Note: The actual value of $k_1 = 2/3$, and the actual value of $t_0 = 4.27$ without nontimber benefits and 4.16 with nontimber benefits. Landowner believes constant fire arrival rate when arrival rate is actually rising with stand age.

[a] In addition to error about shape of fire arrival path.

Concluding remarks

We estimate, for the first time in a forestry context, the value of three types of information about fire risk to a nonindustrial forest landowner. The three types of information are (1) the relationship between fire arrival probabilities and stand age, (2) the magnitude of fire arrival probabilities, and (3) the efficacy of intermediate (fuel reduction) treatment in reducing fire losses. We find that the value of information depends to a large extent on the types and combinations of mistakes a landowner makes, the type of landowner (i.e., whether he undertakes intermediate treatment and whether he values nontimber benefits), and his perceptions about fire risk. The most important distinctions appear to be whether a landowner undertakes intermediate treatment, whether the fire arrival rate is increasing or constant with stand age, and whether multiple mistakes are made.

Information of various types is of most value to a landowner who does not undertake intermediate treatment. The value of information about the overall magnitude of fire risk is also more than twice as high for a landowner who underestimates fire risk. If a landowner undertakes intermediate treatment but makes multiple mistakes, then the asymmetry between overestimating and underestimating fire risk and efficacy of intermediate treatment becomes more pronounced. Our results are striking for this case, in that we find a landowner who underestimates both fire risk and efficacy of intermediate treatment could capture additional maximum expected rents of nearly two orders of magnitude by having accurate information. Landowners who overestimate fire risk and overestimate intermediate treatment efficacy do not gain as much from accurate information, and interestingly, overestimating intermediate treatment efficacy is more important to earning high maximum expected rents high than overestimating fire risk.

Landowners who do not undertake intermediate treatment and those who underestimate fire risk are probably the norm among nonindustrial ownership in the United States. These landowners are least aware that their decisions could affect fire loss and thus stand to gain the most from information dissemination. Educating these landowners about the importance of undertaking fuel reduction could be an important component to any policy effort aimed at minimizing the fire losses of a landowner.

Future research could consider mechanisms for landowners to learn about fire risks and update information over time, which might induce a partial prevention landowner to become a full prevention landowner. The importance of interactions between a government that chooses suppression effort and landowners who choose fuel reduction also remains to be examined. Finally, the nature of intermediate treatment could also be modeled in a more dynamic setting, and fuel reduction implications for a landscape of landowners remain as interesting topics for future research.

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